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A STUDY OF IMPACT RESPONSE OF ELECTRIFIED ORGANIC MATRIX COMPOSITES (PREPRINT)

Robert L. Sierakowski
Air Force Research Laboratory
Munitions Directorate
AFRL/MN CA-N
Eglin AFB, FL 32542-6810

Igor Y. Telichev
Olesya I. Zhupanska
REEF
University of Florida
Shalimar, FL 32579

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14. ABSTRACT

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The existing experimental evidence suggests that organic matrix composites sustain less impact damage when an electric field is applied. The intricate interaction of an electrical field and mechanical load is governed by coupling of the mechanical and electromagnetic fields via the Lorentz force as well as by the processes undergoing at the microscopic level: Joule heat, fiber-matrix interface changes, etc. The current work includes both experimental and theoretical investigations of the effects of an electric current on the impact response of carbon fiber polymer matrix composites.

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A STUDY OF IMPACT RESPONSE OF ELECTRIFIED ORGANIC MATRIX COMPOSITES

Robert L. Sierakowski, Air Force Research Laboratory, Eglin AFB, FL 32542, U.S.A
Igor Y. Telichev, REEF, University of Florida, Shalimar, FL 32579, U.S.A
Olesya I. Zhupanska, REEF, University of Florida, Shalimar, FL 32579, U.S.A

ABSTRACT

The existing experimental evidence suggests that organic matrix composites sustain less impact damage when an electric field is applied. The intricate interaction of an electrical field and mechanical load is governed by coupling of the mechanical and electromagnetic fields via the Lorentz force as well as by the processes undergoing at the microscopic level: Joule heat, fiber-matrix interface changes, etc.

The current work includes both experimental and theoretical investigations of the effects of an electric current on the impact response of carbon fiber polymer matrix composites.

The *experimental part* of the work consists in low velocity impact tests of current carrying composite plates. We have developed a setup that allowed for effective application of an electric current to carbon fiber polymer matrix composites. A series of low velocity impact tests have been performed in order to assess the damage resistance of electrified carbon fiber polymer matrix composites. The tests have been carried out under 0 A, 25 A, and 50 A DC electric currents applied to the composite plates. The results of measurements have shown considerable dependence of the impact-induced damage upon the intensity of the electric field applied to the composite.

The *theoretical part* of the work is concentrated on the analysis of the impact phenomenon in composite plates carrying an electric current. The system of governing equations under consideration consists of equations of motion, Maxwell's equations, and heat transfer equations. We have investigated the effects of Joule heating in composites due to an externally applied electric field, which is especially important for carbon fiber polymer matrix composites because of relatively low electrical conductivity of fibers and thermal conductivity of the matrix. The results indicate that extensive Joule heating leads to significant temperature gradients across the composite plates. Aalysis of the Joule heat effects reveals that it is not a primary mechanism for the strengthening phenomenon observed in the experiments.

INTRODUCTION

The superior stiffness and strength of fiber-reinforced polymer composites make them particularly attractive for high-performance aerospace structures. For instance, the U.S. Air Force's F-22 Raptor consists of 25 percent carbon-epoxy composites by weight, and the developmental Joint Strike Fighter (F-35 Lightning II) will be 25 to 30

percent composite by weight [1]. The reinforced fiber composites have better properties than non-reinforced polymers or conventional metals, and can be used not only as structural materials, but also provide advanced functional behavior through enhanced properties. According to the analysis presented in [2], the fiber-reinforced polymer composites have the highest potential for achieving up to 20-25% performance improvement over the next 15 to 25 years; it is also concluded that monolithic materials are unlikely to achieve property improvements of this magnitude.

The present work was inspired by the experimental results by Snyder et al. [3], who performed a series of impact tests on fiber polymer matrix unidirectional composite plate with and without DC electric current of 20 and 40 A running through the fibers. Their preliminary results provided evidence of strengthening of the composite material and its increased resistance to debris-induced fracture and delamination in the presence of an electric current applied to the composite plates.

The current work presents the experimental and theoretical investigations of the effects of an electric current on the dynamic mechanical response of carbon fiber polymer matrix composites. In the beginning we provide foundations of the theory of electrically and mechanically anisotropic current-conducting solids. We focus our attention on the interacting effects of the mechanical and electromagnetic loads and also Joule heat effects. After that an experimental setup for impact tests of the current-conducting composite panels is described and experimental results on unidirectional and cross-ply carbon fiber reinforced polymer matrix current-carrying composite plates are discussed.

MECHANICAL BEHAVIOR OF COMPOSITES SUBJECTED TO THE MECHANICAL AND ELECTROMAGNETIC LOADS

On the macroscale, the carbon fiber polymer matrix composites are electrically conductive, and consist of electrically conductive carbon fibers and dielectric polymer matrix. Therefore, simultaneous application of mechanical and electromagnetic loads inevitably leads to the coupling of mechanical and electromagnetic fields. Mathematically speaking, the problem reduces to solving of equations of motion and Maxwell's electrodynamic equations, which are coupled through the Lorentz ponderomotive force that represents the effects of an electromagnetic field in the solid body.

In this section we briefly dwell on the field equations for the mechanically and electrically anisotropic solids subjected to the mechanical and electromagnetic loads. All the details of the current discussion and derivations may be found in Zhupanska and Sierakowski [4]. It is well known that there is an interaction of the mechanical and electromagnetic fields in the electrically conductive solids when both mechanical and electromagnetic loads are applied. Equations of motion in the presence of an electromagnetic field are

$$\frac{\partial \tau_{ij}}{\partial x_j} + \rho\left(F_i + F_i^L\right) = \rho \frac{\partial^2 u_i}{\partial t^2} \tag{1}$$

Here τ_{ij} are the stress tensor components, u_i are the displacement components, ρ is

the density of solid body, F_i are the body force components, F_i^L are the components of the Lorentz ponderomotive force that in the case of an electrically anisotropic but magnetically isotropic solid body takes the form

$$\vec{F}^L = \rho_e\left(\vec{E} + \frac{\partial \vec{u}}{\partial t} \times \vec{B}\right) + \left(\boldsymbol{\sigma} \cdot \left(\vec{E} + \frac{\partial \vec{u}}{\partial t} \times \vec{B}\right)\right) \times \vec{B}$$
$$+ \left(\left((\boldsymbol{\varepsilon} - \varepsilon_0 \cdot \mathbf{1}) \cdot \vec{E}\right) \times \vec{B}\right)_\alpha \nabla \left(\frac{\partial \vec{u}}{\partial t}\right)_\alpha + (\vec{J}^* \times \vec{B}), \tag{2}$$

where $\mathbf{1}$ is the unit tensor of the second order, $\boldsymbol{\varepsilon}$ is electrical permittivity tensor, $\boldsymbol{\sigma}$ is electrical conductivity tensor, ε_0 is the permittivity in the vacuum, $\vec{u}$ is the displacement vector, $\vec{D}$ is the electric displacement vector, $\vec{B}$ is the magnetic induction vector, $\vec{E}$ is the electric field vector, ρ_e is the charge density (for electric conductors $\rho_e = 0$), $\vec{j}^*$ is the density of the external electric field, ∇ is the gradient operator, and Einstein's summation convention is adopted with respect to the index α. The third nonlinear term in Eq. (2) is due to anisotropy in electrical properties (it vanishes when electric field is isotropic), and the last term attributes to the electric current that the solid body carries. As one can see, the Lorentz force in composites depends on the external electric and magnetic fields, magnitude and orientation of the electric current with respect to the magnetic field, and velocity and the rate of deformation of the solid.

Maxwell's equations read as

$$\mathrm{div}\vec{D} = \rho_e, \qquad \mathrm{curl}\vec{E} = -\frac{\partial \vec{B}}{\partial t},$$
$$\mathrm{div}\vec{B} = 0, \qquad \mathrm{curl}\vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \tag{3}$$

and equations of the electromagnetic field in electrically anisotropic but magnetically isotropic solids have the form

$$\vec{D} = \boldsymbol{\varepsilon}\vec{E} + \mu\left(\boldsymbol{\varepsilon} - \varepsilon_0 \cdot \mathbf{1}\right)\left(\frac{\partial \vec{u}}{\partial t} \times \vec{H}\right),$$
$$\vec{B} = \mu\vec{H} - \mu\frac{\partial \vec{u}}{\partial t} \times \left(\left(\boldsymbol{\varepsilon} - \varepsilon_0 \cdot \mathbf{1}\right) \cdot \vec{E}\right), \tag{4}$$
$$\vec{j} = \boldsymbol{\sigma}\left(\vec{E} + \frac{\partial \vec{u}}{\partial t} \times \vec{B}\right) + \rho_e \frac{\partial \vec{u}}{\partial t},$$

where μ is magnetic permeability, $\vec{j}$ is the current density vector, and $\vec{H}$ is the magnetic field vector.

The system of governing equations (1) and (3) is essentially nonlinear and coupled in the dynamic problems. But even in static problems, when equations of equilibrium

(1) and Maxwell's equations (3) are not coupled, the Lorentz force (2) may be still present in (1) due to, for example, an externally applied DC current (the last term in (2)). For anisotropic thin plates the system of governing equations (1) and (3) may be reduced to the 2D one by means of the classic Kirchhoff hypothesis of nondeformable normals and the corresponding electromagnetic hypothesis (see, for example [4,5]). The systems of equations (1) and (3) or its 2D approximation constitute a mathematical framework within which a variety of problems involving electro-magneto-mechanical coupling for 3D and 2D bodies may be solved. For example, in [4] the problems of the static and dynamic mechanical response of DC and AC electric current-carrying composite plates in the presence of mechanical load and immersed in the magnetic field are considered. It is shown that electromagnetic field may significantly enhance or reduce the deformed state of the composite plate depending on the direction of its application and its intensity. Although the problems of interaction of mechanical and electromagnetic fields in solids have been studied in the past [5-8], the scope of these problems has been limited mostly to metals and superconductors.

Recently, changes in the local compression and deformation around the low velocity impact zone in a unidirectional current-carrying composite were studied in [9]. In this work the three-dimensional impact and electromagnetic loads induced stresses and displacements have been computed. Analysis of the failure surface around the impact zone suggests that the electromagnetic load may move the failure envelope, which in turn may lead to the composite failure at a higher mechanical load. Therefore, it is possible to amplify or counterbalance the effect of the mechanical load in composites using a specially applied electric current and magnetic field.

JOULE HEAT EFFECTS

Here we discuss Joule heating in composites due to an externally applied electric field. Joule heating is especially crucial in the mechanical response of electrified unidirectional carbon fiber polymer matrix composites that possess relatively low (in comparison to metals) electrical conductivity of fibers and thermal conductivity of the matrix. Our objective is to determine the variation in the temperature across the thickness of the carbon fiber polymer matrix composite plate due to an electric current passing in the carbon fibers.

A long cylindrical carbon fiber embedded in the polymer matrix and heated by DC current I produces Joule heat of the density Q:

$$Q = \frac{(J_x)^2}{\sigma_x^{(f)}}, \tag{5}$$

where J_x is electric current density, $\sigma_x^{(f)}$ is electrical conductivity of the fiber in the fiber direction. The electrical conductivity of the AS4 carbon fibers is $\sigma_x^{(f)} = \frac{1}{1.53} \times 10^3 \, 1/\mathrm{Om\,m}$. In polymer matrix composites, even moderate DC electric currents may lead to significant heating and subsequent alteration in the mechanical response.

In this section we evaluate the effects of Joule heating in electrified carbon fiber polymer matrix composites. The corresponding heat transfer problem between a conducting fiber and an insulator matrix is described by

$$
\begin{aligned}
k_r^{(f)} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T^{(f)}}{\partial r} \right) &= -Q + c^{(f)} \rho^{(f)} \frac{\partial T^{(f)}}{\partial t}, \\
k^{(m)} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T^{(m)}}{\partial r} \right) &= c^{(m)} \rho^{(m)} \frac{\partial T^{(m)}}{\partial t}
\end{aligned}
\tag{6}
$$

with boundary conditions that correspond to the thermal contact resistance between the fiber and matrix

$$
k_r^{(f)} \frac{\partial T^{(f)}}{\partial r} = k^{(m)} \frac{\partial T^{(m)}}{\partial r} = h_{cp}\left(T^{(m)} - T^{(f)} \right). \tag{7}
$$

Here $T^{(f)}$ and $T^{(m)}$ are temperatures in the fiber and matrix correspondingly, $k_r^{(f)}$ is the thermal conductivity of the fiber in the radial direction that is assumed to be transversally isotropic, $k^{(m)}$ is the thermal conductivity of the matrix, which is isotropic, and h_{cp} is the thermal fiber/matrix contact conductance. Note that $h_{cp} = 0$ if there is no thermal resistance between the fiber and matrix, $c^{(f)}$ and $c^{(m)}$ are specific heat of the fiber and matrix correspondingly, and $\rho^{(f)}$ and $\rho^{(m)}$ are fiber and matrix densities. The first equation of (6) must be solved for fibers and the second equation of (6) must be solved for the matrix.

Let us consider unidirectional carbon fiber polymer matrix composite plate that carries a DC current I in the fiber direction. Assume that the ratio of the thickness, h, to the width, a, of the plate is small and Newton's convection takes place at the plate's surfaces $z = \pm h/2$, namely

$$
\left(\frac{\partial T^{(m)}}{\partial y} \right)\Big|_{z=\pm h/2} = h_s \left(T_{\text{outside}} - T^{(m)} \right)\Big|_{z=\pm h/2}, \tag{8}
$$

where h_s is the convection coefficient between the plate and the surrounding air and T_{outside} is the temperature of the surrounding air. The problem (7), (8), (9) for the composite plate is solved using finite element analysis. Due to symmetry considerations instead of the entire plate we consider the strip: $0 \le y \le (r_b + d/2)$, $-h/2 \le z \le h/2$, where r_b is the radius of the fiber bundle and d is the distance between fiber bundles.

The following parameters were used in computations: fiber bundle radius $r_b = 69.444\,\mu m$, fiber bundle spacing $d = 17.361\,\mu m$ (based on 62% fiber volume in the composite), fiber thermal conductivity $k_r^{(f)} = 1.8$ W/mK, matrix thermal conductivity $k_r^{(m)} = 0.2$ W/mK (epoxy matrix), fiber electrical conductivity

$\sigma_x^{(f)} = \frac{1}{1.53} \times 10^3 \, 1/\mathrm{Om\,m}$ (as for AS4 carbon fibers), convection coefficient $h_s = 1000 \ \mathrm{W/m^2K}$, $h_{cp} = 0$, specific heat of the carbon fibers $c^{(f)} = 0.22 \, \mathrm{cal/(g\,K)} = 920.92 \, \mathrm{cal/(kg\,K)}$ at $167^0 \ \mathrm{F} = 75^0 \ \mathrm{C}$, specific heat of the epoxy matrix $c^{(m)} = 0.5 \, \mathrm{cal/g\,K} = 2093 \, \mathrm{cal/kg\,K}$, carbon fibers density $\rho^{(f)} = 1790 \, \mathrm{kg/m^3}$, and the epoxy matrix density $\rho^{(m)} = 1300 \, \mathrm{kg/m^3}$. Computations have been performed for different electric current densities J_x and plate thicknesses h.

Figure 1 shows typical temperature variation across the thickness of the composite plate. As it could be expected, the maximum temperature, $T_{\max}$, reaches in the middle of the plate ($z = 0$), the minimum temperature, $T_{\min}$, is at the surface, $z = \pm h/2$. Moreover, a strong temperature gradient appears in carbon fiber polymer matrix composite plates as a result of application of a DC electric current.

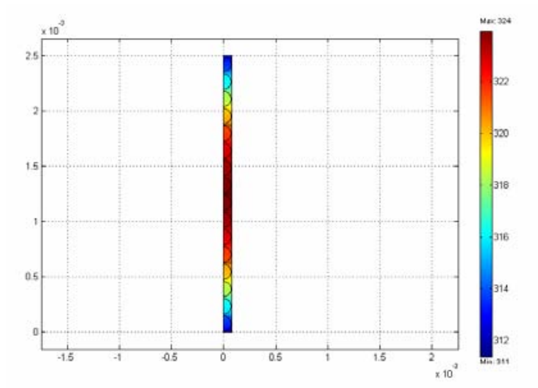


Figure 1. Temperature profile across the composite plate thickness.

It is worth noting that for the given volume of fibers in the composite and for electric current densities $J_x > 5 \times 10^4 \ \mathrm{A/m^2}$ the temperature in the matrix in the middle of the plate is practically the same as the temperature in the neighboring fiber bundle. Figure 2 shows the temperature jump $T_{\min} - T_{\mathrm{outside}}$ at the composite plate surface as a function of the plate thickness h under different current densities J_x. As one may see there is strong nonlinear dependence between the electric current density and an increase in the temperature at the composite plate surface.

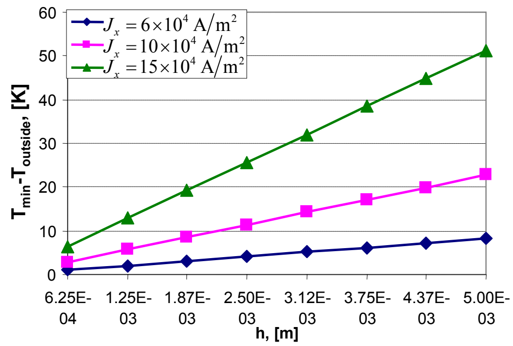


Figure 2. Temperature jump at the plate surface vs. Plate thickness.

Figure 3 shows the difference in the temperature in the middle of the plate ($T_{\max}$) and the plate surface ($T_{\min}$) as a function of the plate thickness under different current densities J_x.

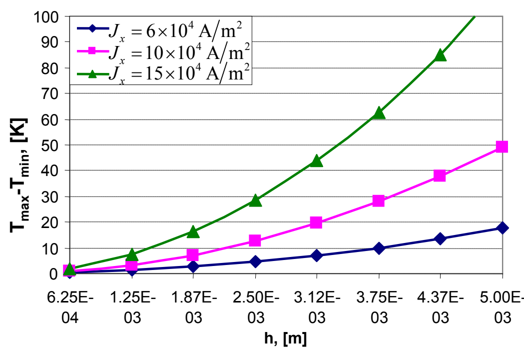


Figure 3. The difference in temperature in the middle of the plate and at the plate surface vs. Plate thickness.

Results show that Joule heating leads to the significant temperature gradients across the composite plate. For example, in the composite plate of thickness $h = 0.005\,\text{m}$, the temperature at the plate surface $T_{\max} = 316.91\,\text{K} = 43.76^0\,\text{C}$ but at the same time temperature in the middle of the plate can reach as high as $T_{\max} = 366.0676\,\text{K} = 92.92^0\,\text{C}$, when the electric current density is $J_x = 10\times10^4\ \text{A}/\text{m}^2$. This may change, for example, the polymer matrix response from elastic to viscoelastic. Moreover, the thermal stresses cannot be ignored in such situation. Note that such temperature gradients correspond to the moment of time when the temperature in the composite plate reaches steady state. Short time applications of the DC current would not produce such large temperature changes, but still some temperature gradient across the plate thickness would arise. We have analyzed Joule heat effects in the polymer matrix composite plates in order to understand the phenomenon and design better the experiments.

The next sections contain the description of the experimental setup and discussion of the experimental results of the impact tests on the electrified carbon fiber polymer matrix composites.

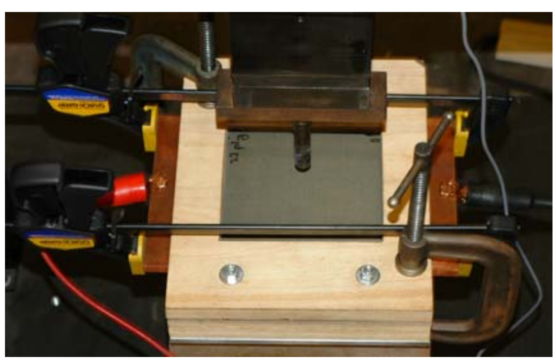
EXPERIMENTAL SETUP

The target specimens were planar carbon fiber reinforced plastic plates with cross-ply and unidirectional layouts. The plates' thickness was 0.18 in (4.5 mm) with 32 plies respectively of carbon fiber mats with dimensions of about 6×6 in (152.4×152.4 mm).

Drop Weight Impact Tester Instron 8120 has been used for impact tests. The mass of falling weight was 225 lb in all experiments. In order to avoid electrical contact between the striker and an impacted plate, a flat-ended cylindrical striker partially fabricated of dielectric DELRIN® plastic was used. The diameter and length of the striker were 0.5 in and 3.0 in respectively.

An electric current was applied prior to each impact test by means of a regulated DC Power Supply, Model HP 6012B. The experimental setup is shown in Figure 4. A wooden-aluminum plate clamping device was used to provide an electrical contact of the composite coupon with copper bus bars, the contacting edges of the plates were coated with silver filled epoxy.

a)



b)

Fig. 4. Impact testing setup.

EXPERIMENTAL RESULTS

Unidirectional Composite Plates

The tested specimens were 6 x 6 in graphite epoxy composite plates with thickness 0.18 in (32 plies). The tests were conducted with no electric current and with DC current of 25 and 50 A applied to the composite plate. These impact tests were performed at conventional V_{50} velocity. This critical impact velocity has been determined in a series of preliminary experiments where two successive impact velocities were determined: the first one corresponded to the complete perforation of the plate and the other one leaded to failure of the plate without perforation. The latter velocity was taken as V_{50}. The measured difference in magnitude of these two successive velocities was 1 ft/s. All conducted impact tests were fully instrumented. The results of testing are presented in Table I. Figure 5 shows the composite plates and the corresponding damage incurred during the impact tests.

TABLE I. EXPERIMENTAL DATA ON UNIDIRECTIONAL PLATES

Test No.	Amperage [A]	Temperature [ºF]	Impact velocity [ft/s]	Maximum load [lb]	Total energy, [ft-lb]	Perforation status
UD-2	0	69.3	2.70	719.30	39.74	No
UD-4	25	69.3	2.65	881.60	37.39	No
UD-7	50	69.3	2.65	1005.09	36.55	No

a) b) c)

Fig. 5. Impacted unidirectional composite plates: a) I=0 A; b) I=25 A; c) I=50 A (height=1.4" (3.5 cm); velocity=2.7 ft/sec; temperature=69.3ºF).

Figure 6 illustrates the evolution of impact response of the unidirectional composite plate without and with a DC electric current applied to the plate in the fiber direction. Figure 7 shows force-displacement relationships for the same composite plates. As one can see, application of the electric current increases plate's resistance to impact induced damage. When an electric current of 20 and 50 A was applied to the composite plate, the maximum load, sustained by the composite plate, increased up to 24.7% and 43.6% respectively. Moreover, both incipient and maximum loads increase when an electric current applied. Note that the electric current was applied immediately before the impact test.

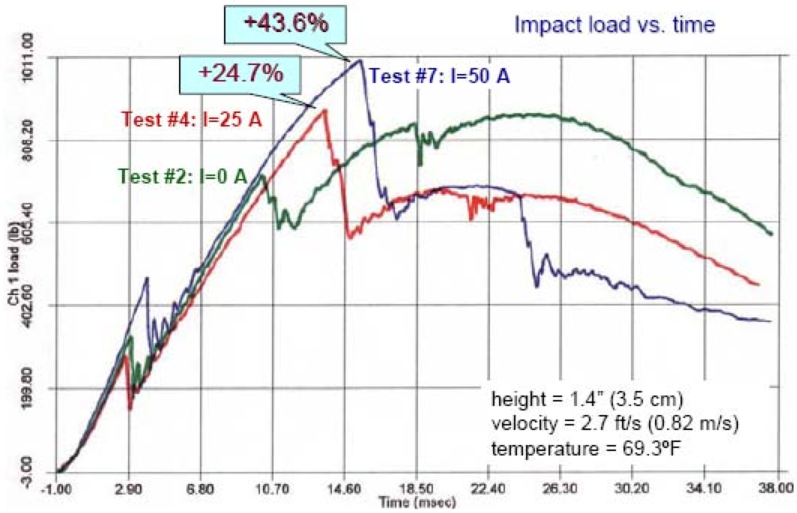


Fig. 6. Evolution of the impact response of unidirectional composite plate without and with a DC electric current applied to the plate in the fiber direction.

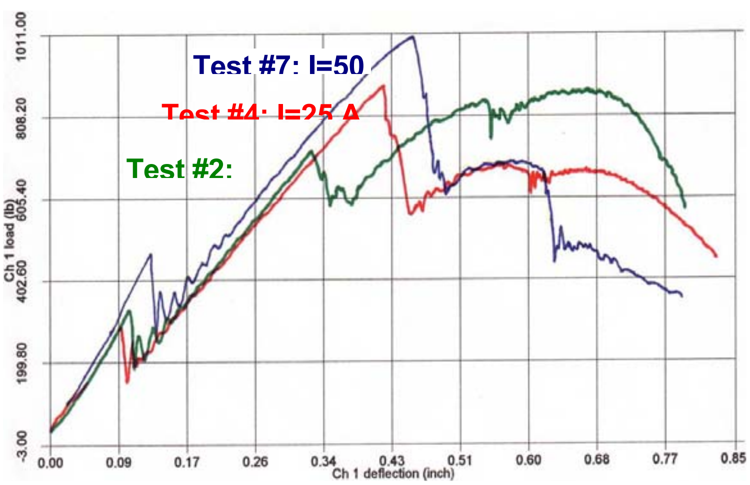


Fig. 7. Force-displacement relationships of unidirectional composite plate without and with a DC electric current applied to the plate in the fiber direction and subjected to the impact load.

The density of magnetic flux was measured by Hall Effect Gussmeter using transverse and axial magnetic field probes. The results of measurements are illustrated in Fig. 8. The probes (both types) were mounted at h=0.16 in (4 mm) above the plate surface. The observed trend was fairly reasonable: as it is seen, there is an increase of B_z and B_y-components with an increase of amperage; the magnitude of B_x-components is almost negligible. In order to estimate the effect of altitude of the probe, an additional measurement of B_z-components was done for h=0.79 in (20 mm). The results are presented in Fig. 9. As one can see, there is a significant decay of the magnetic flux density with the distance from the plate surface, for h=0.16 in (4 mm) the magnitude of B_z is 1.8 times greater than that at h=0.79 in (20 mm).

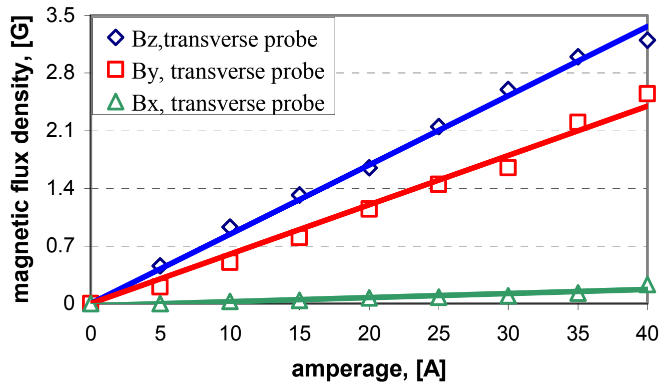


Fig. 8. Magnetic flux density at h=0.16 in (4 mm) as function of the applied current for 32-ply unidirectional graphite epoxy plate.

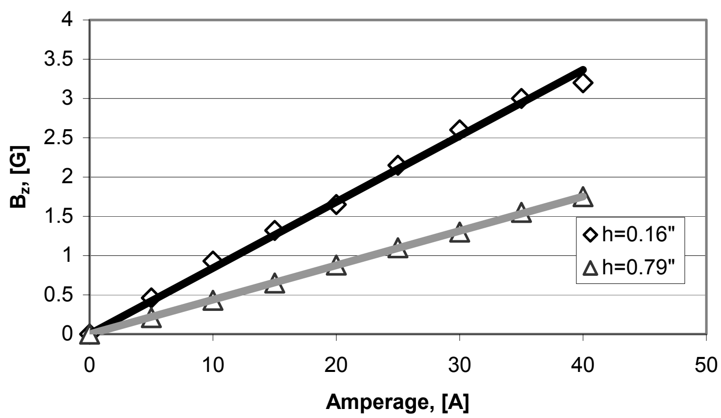
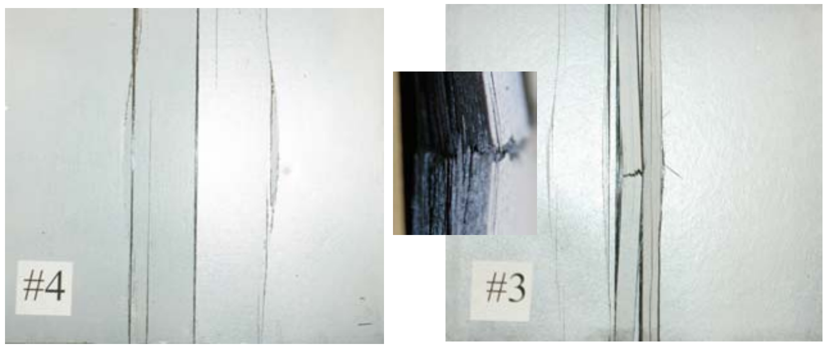


Fig. 9. B_z flux component data at h=0.16 in (4 mm) and h=0.79 in (20 mm) for 32-ply unidirectional graphite epoxy plate.

The previously discussed impact tests were conducted immediately after application of an electric current. So we have not observed any temperature change at the plate surfaces due to a passing current. The measured temperature at the plate surfaces was around 70°F (21°C) before and after an impact test.

In order to evaluate Joule heat effects due to DC current we have performed somewhat different tests. In these tests, 25 A DC current had been applied to the composite plate until temperature in the plate reached a steady state (for considered 32-ply composite plates it took 24 min to reach steady state temperature of the 96.7°F (35.94°C) in the center of the plate surface). After this, an impact test was performed at a conventional ballistic limit velocity V_{50} =2.7 ft/s (0.82 m/s) determined in the experiments when no current was applied to the plate. The results are shown in Figs. 10, 11, and Table II. Figure 10 shows the backside of the impacted composite plates. Figure 11 illustrates the evolution of the impact response of the unidirectional composite plates carrying 25 A DC current for short period of time (red line) and for 24 min before the actual impact test was carried out (blue line).



a) b)

Fig. 10. Impacted unidirectional composite plates: a) test #UD-4, T=69.3 F; b) test #UD-3, T=96.7 F

TABLE II. EXPERIMENTAL DATA ON UNIDIRECTIONAL PLATES

Test No.	Amperage [A]	Temperature [ºF]	Impact velocity [ft/s]	Maximum load [lb]	Total energy [ft-lb]	Perf. Status
UD-3	25	96.7	2.65	936.02	30.05	Yes
UD-4	25	69.3	2.65	881.60	37.39	No

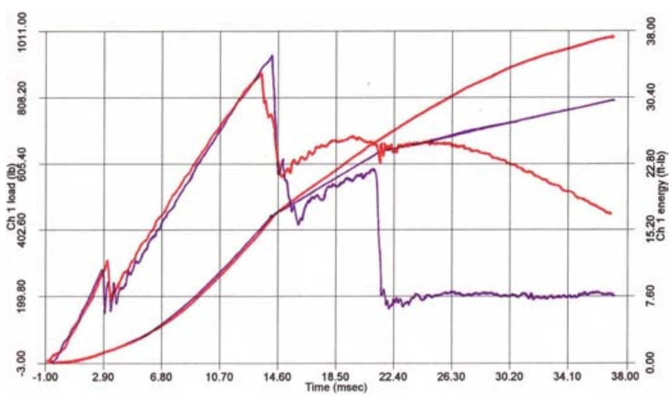


Fig. 11. Evolution of the impact response of composite plate carrying a 25 dc electric current: red lines – current was applied immediately before the impact, blue lines – current was applied for 24 min. Before the impact.

As one can see the Joule heat has a distinct effect on the failure mode. Short application of the electric current (specimen # 4) led to the polymer matrix failure along the fiber direction, and an extensive application of the current caused significant Joule heating of the composite plate which resulted in the "localization" of the damage zone (perforation of the plate across the fibers) and both fiber and matrix failure (specimen #3). Further we notice that according to our analysis of the Joule heating in the carbon fiber polymer matrix composite plate discussed above, there is a large temperature gradient in the plate #3 due to extensive application of the DC current. Under the conditions of the experiment #3 we may expect a 30°C difference in the temperature in the middle of the plate and at the plate surface. Therefore, if the

measured temperature at the surface of the plate was 35.94°C, the temperature in the middle of the plate is expected to be about 66°C.

Although an extensive application of the DC electric current increased the maximum load sustained by the plate (see the spikes between 10.7 ms and 14.6 ms), the subsequent failure induced a considerable drop in the amount of impact energy absorbed by the plate (see the red (no Joule heating) and blue (extensive Joule heating) lines on the right of the Fig. 11). The Joule-heated plate absorbed 24.4% less energy comparing to the plate that carried a DC current only briefly before the impact.

Based on these experiments, we can draw a preliminary conclusion that Joule heating is not a primary factor responsible for the increase in the impact resistance of current carrying composites.

Cross-ply Composite Plates

The impact tests were conducted on [0/90] graphite epoxy composite plates with thickness 0.18 in (32 plies). The tested specimens were 6x6 in square plates; an electric current was applied immediately prior to each impact test by means of a DC load regulated supply (40 V).

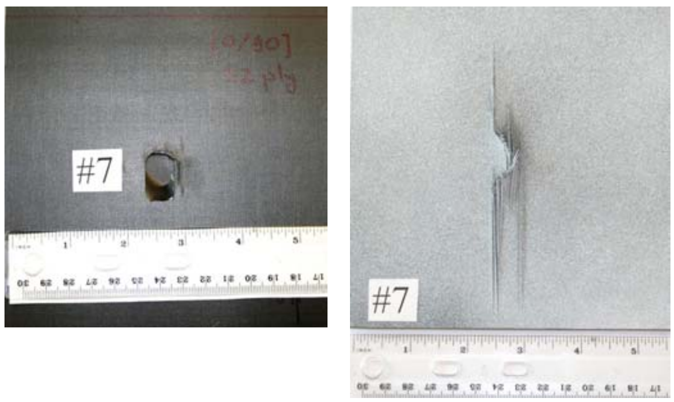
The tests were conducted with no electric current and with DC current of 25 and 50 A applied to the composite plates in either 0º or 90º fiber direction. These impact tests were performed at around V_{50} velocity, 5.2 ft/sec, determined in a series of preliminary experiments. All conducted impact tests were fully instrumented. The summary of experimental results is shown in Table III.

TABLE III. EXPERIMENTAL DATA ON CROSS-PLY PLATES

Test No.	Elect. Current Directio n	Amperage [A]	Impact Velocity [ft/sec]	Max. load [ft]	Absorb. Energy [ft-lb]	Temper. on surface **[ºF]**	Perfor. Status
CP-4	0º	0	5.18	2674.04	67.12	74.2	Yes
CP-7	0º	0	5.20	2618.94	91.31	74.2	No
Av.			5.19	2646.49	79.22		½
CP-5	0º	25	5.21	2808.02	72.66	74.2	Yes
CP-6	0º	25	5.2	3152.2	96.44	74.2	No
Av.			5.205	2980.11	84.55		½
CP-9	0º	50	5.18	3029.61	105.78	74.2	No
CP-10	0º	50	5.15	2906.08	95.45	74.2	No
Av.			5.17	2967.845	100.615		0/2
CP-15	90º	0	5.16	2612.57	105.4	74.2	No
CP-16	90º	0	5.17	2596.05	68.54	74.2	Yes
Av.			5.17	2604.31	86.97		1/2
CP-13	90º	25	5.18	2613.98	106.8	74.2	No
CP-14	90º	25	5.16	2736.26	69.45	74.2	Yes
Av.			5.17	2675.12	88.13		1/2
CP-11	90º	50	5.2	2675.6	106.92	74.2	No
CP-12	90º	50	5.18	2795.2	106.21	74.2	No
Av.			5.19	2735.40	106.57		0/2
CP-17	0	50	5.23	2192.11	96.40	158.0	No
CP-18	0	50	5.25	2107.56	93.83	157.1	No

Av.			5.24	2149.84	95.12	157.6	0/2
#19	0	0 (50)	5.20	2519.35	64.42	--	Yes
#20	0	0 (50)	5.25	2966.29	92.98	--	No
Av.			5.23	2742.82	78.70		0/2

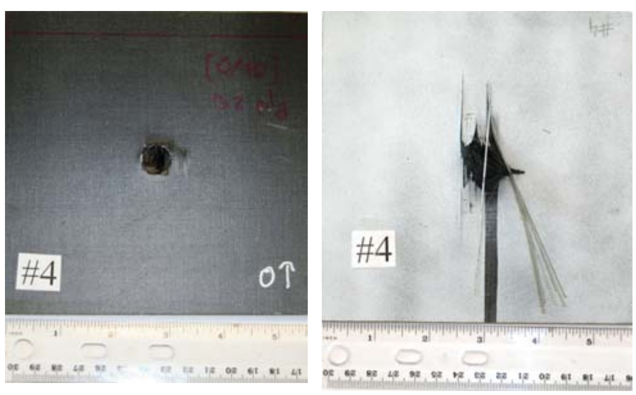
Figure 12 illustrates the impacted composite plate without an electric current applied. Two of the four conducted impact tests have resulted in perforation of specimens. In the case when the plate was not perforated (test #CP-7), an indentation at the front surface of plate was observed (Fig. 12a). The depth of the indentation was approximately 0.14 in. As a result, the backside of the plate exhibited severe damage in the form of delamination and matrix and fibers failure (Fig. 12b).



a) b)

Fig. 12. Impacted cross-ply plates at I=0 A, non-perforation (test #CP-7): a) front side; b) back side.

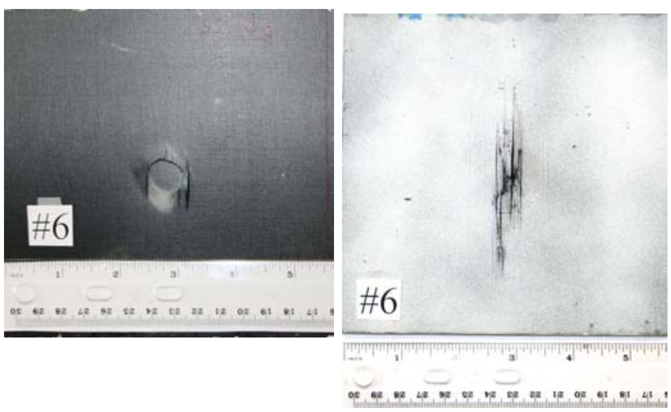
Figure 13 illustrates the failure pattern for perforated plates (test #CP-4).



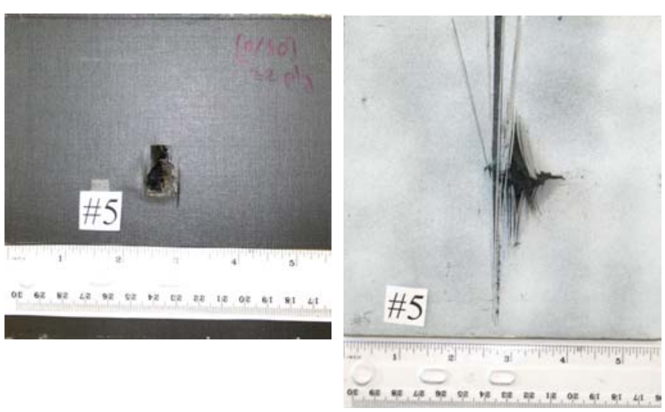
a) b)

c)
Fig. 13. Impacted cross-ply plates at I=0 A, perforation (test #CP-4): a) front side; b) back side; c) side view.

We have carried out impact tests for electrified composite plates carrying a 25 A DC electric current in either 0º or 90º fiber direction. Two plates were perforated and the other two were not. The failure pattern in the presence of 25 A was similar to the case when no electric current was applied to the plate. Non-perforated plates had delamination and cracks on the back and indentation in the front side. However, the depth of this indentation was 0.06 in, which is about two times smaller than that observed in test #CP-7 with no current applied to the plates. The photos of damaged plates are shown in Figs. 14, 15.



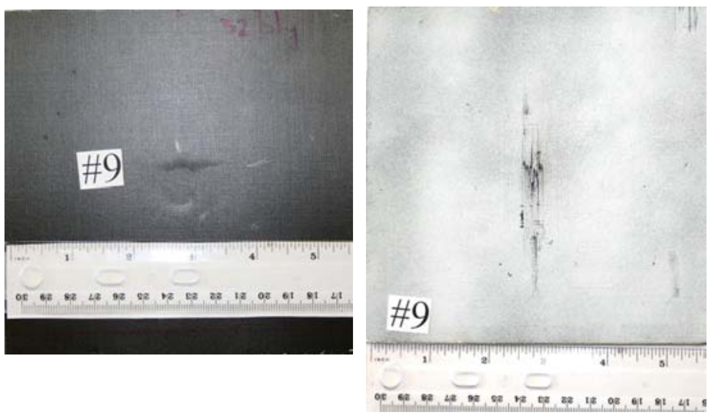
a) b)
Fig. 14. Impacted cross-ply plates at I=25 A, non-perforation (test #6): a) front side; b) back side.



a) b)

c)
Fig. 15. Impacted cross-ply plates at I=25 A, perforation (test #5): a) front side; b) back side; c) side view.

When a 50 A DC electric current was applied to the composites, none of the four specimens was perforated. The front side of impacted plates exhibited slight circular imprint of the striker and did not get any indentation (Fig. 16). Although the failure pattern at the backside of the plates looked similar to the one observed for the case of the 25 A current, the failure itself was less severe (see Fig. 15 for comparison).



a) b)

c)

Fig. 16. Impacted cross-ply plates at I=50 A, non-perforation (test #9): a) front side; b) back side; c) side view.

Our experimental results show insignificant increase in the maximum load sustained by the electrified cross-ply composite plates comparing to the plates with no electric current applied. This fact can be related to a weaker magnetic field created by an electric current passing through the cross-ply plates compared to the magnetic field created by the same current passing in unidirectional composite plates.

The results of the measurements of magnetic flux density are shown in Fig. 17. The measurements were performed using axial magnetic field probe mounted in h=0.16” (4 mm) above the plate surface.

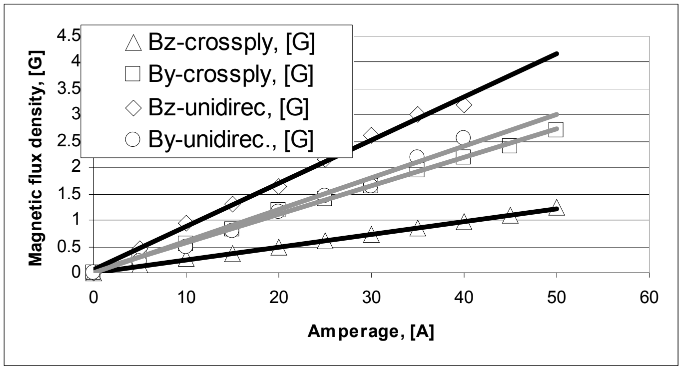


Fig. 17. Magnetic flux density at h==0.16" (4 mm) as a function of the applied current for 32-cross-ply unidirectional graphite epoxy plate.

As one can see, the measured z -component of the magnetic flux density for the cross-ply plate is three times less than that for the unidirectional plate (see Fig. 8).

Figure 18 illustrates the evolution of the composite plate response for the case of I=0 and 50 A current applied. Although in both cases the plates were not perforated and difference between maximum loads was very small, the plates responded differently in the case of I=0 and I=50 A current (see the load curves after reaching the maximums). These different responses led to the indentation on the front side of the plate in the case of I=0 A (Fig. 15) and no indentation in the case of 50 A (Fig. 16). Note that the electric current was applied immediately before the impact test.

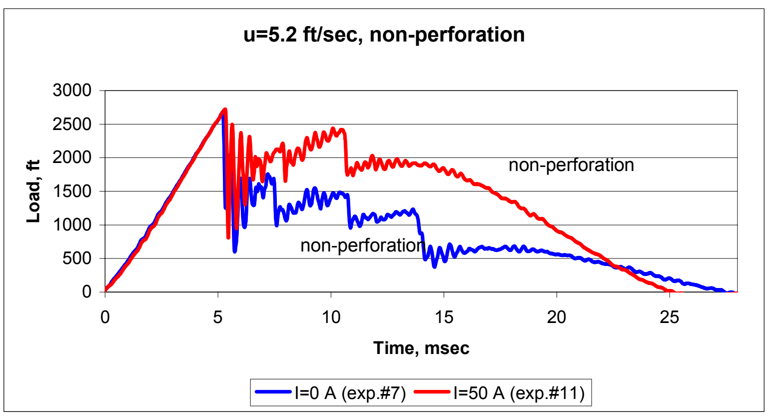
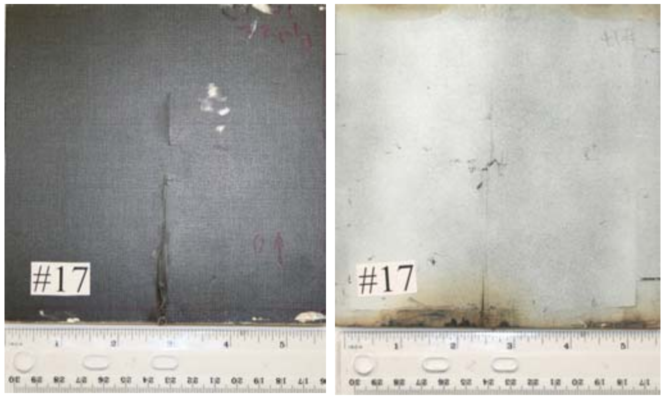


Fig. 18. Impact load history for the cross-ply composite plates for I=0 A (test #CP-7) and I=50 A (test #CP-11).

We have also monitored the energy absorbed by the plates during the impact. For example, it was determined that composites plates carried a 50 A DC electric current absorbed almost 20% more energy during the impact.

As in the case of unidirectional composite plates we have also investigated the effect of Joule heating on the impact response of cross-ply composite plates. In first two tests (#CP-17 and #CP-18), a 50 A DC current had been applied to the composite plate until the temperature in the plate reached a steady state. For the tested plate it took 36 min to reach steady state temperature of the 158°F in the middle of the plate surfaces. After this, an impact test was performed with the current still passing in the plate. None of the specimens was perforated and no indentation was formed. Only a

long crack run from the contact point of the striker and plate to the edge of the composite plate (Fig. 19) was visible after the impact.



a) b)

Fig. 19.Impacted cross-ply composite plates at I=50 A , T=158 °F , non-perforation (test #CP-17): a) front side; b) back side.

In other two experiments the electric current was applied for 3 sec and switched off just before the impact. One of the composite plates was perforated (test #CP-19) and the other one was not (#CP-20), so the result was the same as with no electric current applied and under a 25 A DC current. Therefore, for the cross-ply composite plates we can draw a preliminary conclusion that Joule heating is not a primary factor in the increased impact resistance of electrified composites.

CONCLUSIONS

- A new experimental setup for study of the impact response of composites in the presence of an electric field is developed.
- Application of an electric current of 20 and 50 A to the unidirectional composite plates caused the increase of maximum load, sustained by the composite plate, up to 24.7% and 43.6%, respectively.
- Application of an electric current to the cross-ply composite plate led to insignificant decrease in the maximum load sustained by the plate and significant decrease of the damage zone.
- Analysis of the Joule heat effects reveals that it is not a primary mechanism for the strengthening phenomenon observed in the experiments.

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